

# Higgs couplings with Flavon-Higgs mixing effects in Multi-Scalar models

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Testing the couplings of the Higgs-like particle with  $m_h = 125 - 126$  GeV discovered at the LHC, is one of the most important tasks of High Energy Physics. Current measurements of its properties, seem consistent with the Standard Model (SM), where the Higgs couplings to fermions and gauge bosons, as function of the particle mass, are predicted to lay on a single line. However, in models with extended Higgs sector, fermion couplings for up, down-quarks and leptons, could lay on different lines. We describe all of these possibilities, within the context of a model with 3+1 Higgs doublets. This model includes mixing of the Higgs doublets with a Flavon field, which generates the Yukawa hierarchies and induces Flavor-violating Higgs couplings at acceptable rates. Constraints on the model are derived from the Higgs search at LHC, and their implications for FCNC top decays are presented too.

## I. INTRODUCTION

Particle Physics is currently facing an exciting time. On the one side, we have witnessed the historic discovery of a Higgs-like particle with  $m_h = 125 - 126$  GeV at the LHC [1, 2], which has provided a definite test of the mechanism of Electro-Weak symmetry breaking [3]. Furthermore, this mass value agrees quite well with the range preferred by the electroweak precision tests [4], which confirms the success of the Standard Model (SM). Current measurements of its spin, parity, and couplings, seem also consistent with the SM. The fact that LHC has verified the linear realization of spontaneous symmetry breaking (SSB), as included in the SM, could also be taken as an indication that Nature likes scalars.

On the other hand, the LHC has not detected, so far, any sign of Physics Beyond the SM (PBSM), which has been conjectured in order to address some of the problems left open by the SM, such as hierarchy, flavor, unification, etc [5]. Indeed, the LHC has provided bounds on the new physics scale ( $\Lambda$ ), which are now entering into the TeV range. This is bringing some discomfort, and casting some doubts about the theoretical motivations for new physics scenarios with a mass scale of order TeV, which otherwise should had shown up at LHC. This is particularly disturbing for the concept of naturalness, and its supersymmetric implementation, since the bounds on the mass of superpartners are passing the TeV limit too [6, 7]. However, one has to wait for the next LHC run, with higher energy and luminosity, in order to have stronger limits, both on the search for new particles, such as heavier Higgs bosons [8–10] or others, and for precision tests of the SM properties.

In particular, it will be very important to study the Higgs couplings at LHC and future colliders, in order to test the Higgs identity. Being the remnant of SSB, the Higgs particle couples to a pair of massive gauge bosons, with an strength proportional to its mass. As the Higgs doublet induces the fermion masses too, its couplings with fermions is also proportional to the fermion mass; these are flavor-conserving (FC) couplings. However, so far LHC has tested only a few of these couplings, i.e. the ones with the heaviest SM fermions and  $W, Z$ . Then, some questions arise immediately:

- Do the masses of all fermion types (up-, down-quarks and leptons) arise from a single Higgs doublet? or, are there more Higgs multiplets participating in the game?
- Are the Higgs couplings to fermions diagonal in flavor space?
- Is there any hope to measure the Higgs couplings with the lightest quarks and leptons?

Non-standard Higgs couplings, including the flavor violating (FV) ones, are predicted in many models of physics beyond the SM, for instance in the general 2HDM [11–13]. In particular, extensions of the SM that contain additional scalar fields, which have non-aligned couplings to the SM fermions and mix with the Higgs boson, will induce new FV Higgs interactions at tree-level. This transmission of the flavor structure to the Higgs bosons, was called *a more flavored Higgs boson* in our earlier work [14]. Mixing of SM fermions with exotic ones, could also induce FV Higgs couplings at tree-level [15]. It could also happen that the Higgs sector has diagonal couplings to the SM fermions at tree-level, but the presence of new particles with a non-aligned flavor structure, which couple both to the Higgs and to the SM fermions, will induce corrections to the Yukawa couplings and/or new FCNC process at loop levels.

This is realized for instance in supersymmetry, where the sfermion/gauginos can have non-diagonal couplings to Higgs bosons and SM fermions [14].

After LHC delivered the Higgs signal, many papers have been devoted to study non-standard Higgs couplings, and the constraints on deviations from SM [34–38]. Although such deviations could be discussed within an effective lagrangian approach, it is also important to discuss them within an specific model, where such deviations could be interpreted and given a context. In this paper, we discuss the generic parameterization of FC Higgs couplings, as arising from a model that includes 3+1 Higgs doublets. Further, we also include mixing among the Higgs sector and a Flavon field, which induces FV Higgs couplings.

We present first (Section 2), the Yukawa lagrangian of the model, and identify several scenarios that could be studied at future colliders. Within the SM, the Higgs couplings to fermions and gauge bosons, as function of the particle mass, lay on a straight line. However, we will show that in our model, fermion couplings could lay on distinct lines. In section 3, we discuss the LHC constraints on the parameters of the model; for this part, we shall rely on the results of reference [16]. Then, the implications of FV Higgs couplings are presented in section 4, focusing on the top quark FCNC transitions  $t \rightarrow ch$ . Concluding remarks are included in section 5, including a brief discussion about the search for the flavon particle itself at VLHC, and the possible ways to test the Higgs couplings with the lightest fermions.

## II. HIGGS COUPLINGS WITHIN A 3+1 HIGGS MODEL

Thus, we shall consider for definitiveness, a four-Higgs doublet model, which are denoted as  $\Phi_0, \Phi_1, \Phi_2, \Phi_3$ . We shall impose a discrete symmetry in such a way that one doublet ( $\Phi_0$ ) is of the inert-type, and therefore the lightest particle within this doublet is stable, and becomes a viable (Scalar) Dark matter condidate [19]. This is just a declaration of principles, as we shall not explore here the constraints on the model from searches for Dark Matter. However, a simpler model with 2+1 Higgs doublets has been discussed in ref. [20], which includes extra sources for CP violation and has a rich phenomenology, which also improves the IDM model [21]; we shall come back to the study of DM implications in future work. Then, each Higgs doublet ( $\Phi_a$ ) is responsible for giving masses to a fermion type, i.e.  $\Phi_1$  gives masses to up-type quarks, while  $\Phi_2$  and  $\Phi_3$  give masses to d-type quarks and leptons, respectively.

This model implies that the Higgs couplings could deviate from the SM predictions. The Higgs couplings to gauge bosons deviate from the SM, because the model includes several doublets developing a vev, while the diagonal Yukawa couplings show deviations because fermion masses are generated by a different Higgs doublet. Furthermore, we shall also include an SM singlet, which participates in the generation of the Yukawa hierarchies, a la Froggatt-Nielsen, and thus has FV couplings. This singlet mixes with the Higgs doublets, and induces FV Higgs couplings. The case with mixing of the SM Higgs doublet with a flavon singlet, and its phenomenology, has been studied in ref. [17]. Besides serving us as a specific model to test the pattern of Higgs couplings, and new physics, ou 3+1 model can be motivated from the scenarios having one Higgs for each generation, such as the  $E_6$  GUT model and the superstring-inspired models.

### A. Yukawa lagrangian for a multi-Higgs model with Flavon-Higgs mixing

We start with the Yukawa lagrangian, a la Froggatt-Nielsen, given by:

$$\mathcal{L}_Y = \rho_{ij}^u \left(\frac{S}{\Lambda_F}\right)^{n_{ij}} \bar{Q}_i d_j \tilde{\Phi}_1 + \rho_{ij}^d \left(\frac{S}{\Lambda_F}\right)^{p_{ij}} \bar{Q}_i u_j \Phi_2 + \rho_{ij}^l \left(\frac{S}{\Lambda_F}\right)^{q_{ij}} \bar{L}_i l_j \Phi_3 + h.c. \quad (1)$$

where  $n, p, q$  denote the charges of each fermion type under some unspecified Abelian flavor symmetry, which will help to explain the fermion mass hierarchy. The field  $S$  is a complex Flavon field, while  $\Lambda_F$  denotes the Flavor scale and  $\rho_{ij}^f$  ( $f = u, d, l$ ) are some  $O(1)$  coefficients. The Higgs doublets are written as:  $\Phi_i = (\Phi_i^+, \Phi_i^0)^T$ .

We shall expand to linear order in the Flavon terms ( $S = \frac{1}{\sqrt{2}}(u + s_1 + is_2)$ ), as follows:

$$\left(\frac{S}{\Lambda_F}\right)^{n_{ij}} = \epsilon_F^{n_{ij}} \left(1 + \frac{n_{ij}}{u}(s_1 + is_2)\right) \quad (2)$$

where  $\epsilon_F = \frac{u}{\sqrt{2}\Lambda_F} \simeq 0.22$ , is of the order of the Cabibbo angle.

The effective lagrangian will be written, keeping only the neutral Higgs components ( $\Phi_i^0$ ), as follows:

$$\begin{aligned}\mathcal{L}_Y = & Y_{ij}^u \bar{u}_i u_j \Phi_1^0 + Y_{ij}^d \bar{d}_i d_j \Phi_2^0 + Y_{ij}^l \bar{l}_i l_j \Phi_3^0 + \\ & [Z_{ij}^u \bar{u}_i u_j \Phi_1^0 + Z_{ij}^d \bar{d}_i d_j \Phi_2^0 + Z_{ij}^l \bar{l}_i l_j \Phi_3^0] \frac{1}{u} (s_1 + i s_2) + h.c.\end{aligned}\quad (3)$$

where the Yukawa matrix is given as:  $Y_{ij}^f = \rho_{ij}^f (\epsilon_F)^{n_{ij}^f}$ , while the Flavon interactions are described by the matrix:  $Z_{ij}^f = \rho_{ij}^f n_{ij}^f (\epsilon_F)^{n_{ij}^f}$ .

Then, substituting  $\Phi_i^0 = \frac{1}{\sqrt{2}}(v_i + \phi_i^0 + i\chi_i^0)$ , we can identify the mass terms and the yukawa and flavon interactions. We need to diagonalize the fermion mass matrices, by the usual bi-unitary rotations. Here we shall assume the Yukawa matrix is symmetric. Furthermore, we shall write here only the interaction lagrangian for the real components of the neutral Higgs fields:

$$\begin{aligned}\mathcal{L}_Y = & \bar{U} \frac{M_u}{\sqrt{2}v_1} U \phi_1^0 + \bar{D} \frac{M_d}{\sqrt{2}v_2} D \phi_2^0 + \bar{L} \frac{M_l}{\sqrt{2}v_3} L \phi_3^0 \\ & + [\frac{v_1}{u} \bar{U} \tilde{Z}^u U + \frac{v_2}{u} \bar{D} \tilde{Z}^d D + \frac{v_3}{u} \bar{L} \tilde{Z}^l L] s_1 \\ & + [\bar{U} \tilde{Z}^u U \phi_1^0 + \bar{D} \tilde{Z}^d D \phi_2^0 + \bar{L} \tilde{Z}^l L \phi_3^0] \frac{1}{u} s_1\end{aligned}\quad (4)$$

The matrices  $\tilde{Z}^f$  are written now in the mass-eigenstate basis, and in general are not diagonal, and thus they will induce FCNC mediated by the Higgs field. The capital letters for (Dirac) fermion fields are used to indicate the vector of mass eigenstates, i.e.  $U_i = (u, c, t)$ ,  $D_i = (d, s, b)$ ,  $L_i = (e, \mu, \tau)$ .

Then, the Higgs and Flavon fields are written in terms of mass eigenstates, through the rotation  $O^T$  of dimensions  $(4 \times 4)$ :

$$\begin{aligned}Re\Phi_i^0 &= O_{i1}^T h_1^0 + O_{i2}^T H_2^0 + O_{i3}^T H_3^0 + O_{i4}^T H_F^0 \\ ReS &= O_{41}^T h_1^0 + O_{42}^T H_2^0 + O_{43}^T H_3^0 + O_{44}^T H_F^0\end{aligned}\quad (5)$$

The details of the diagonalization depend on the Higgs potential, however as one can see from the discussion of refs. [22, 23], there are plenty of parameters to have a reasonable particle spectrum, including the decoupling limit, such as the one we shall discuss here. Furthermore, as the vev's must satisfy:  $v_1^2 + v_2^2 + v_3^2 = v^2$ , with  $v = 246$  GeV, we find convenient to use spherical coordinates to express each vev ( $v_i$ ) in terms of the total vev  $v$  and the angles  $\theta$  and  $\phi$ , namely:  $v_1 = v \cos \theta$ ,  $v_2 = v \sin \theta \cos \phi$  and  $v_3 = v \sin \theta \sin \phi$ .

Thus, for the lightest Higgs state, which is identified as  $h^0 = h_1^0$ , one has finally the following interaction lagrangian for the Higgs-fermion couplings,

$$\mathcal{L}_Y = [\frac{\eta^u}{v} \bar{U} M_u U + \frac{\eta^d}{v} \bar{D} M_d D + \frac{\eta^l}{v} \bar{L} M_l L + \kappa^u \bar{U}_i \tilde{Z}^u U_j + \kappa^d \bar{D}_i \tilde{Z}^d D_j + \kappa^l \bar{L}_i \tilde{Z}^l L_j] h^0 \quad (6)$$

where:  $\eta^u = O_{11}^T / \cos \theta$ ,  $\eta^d = O_{21}^T / \sin \theta \cos \phi$ ,  $\eta^l = O_{31}^T / \sin \theta \sin \phi$ , describe the strength of the flavor-diagonal Higgs couplings. While the FV Higgs couplings are described by the parameters:  $\kappa^u = \frac{v}{u} O_{41}^T \cos \theta$ ,  $\kappa^d = \frac{v}{u} O_{41}^T \sin \theta \cos \phi$ ,  $\kappa^l = \frac{v}{u} O_{41}^T \cos \theta \sin \phi$ .

Besides the Yukawa couplings, we also need to specify the Higgs couplings with vector bosons, which is written as  $g_{hVV} = g_{hVV}^{sm} \chi_V$ , with the factor  $\chi_V$  given as:

$$\begin{aligned}\chi_V &= \frac{v_1}{v} O_{11}^T + \frac{v_2}{v} O_{21}^T + \frac{v_3}{v} O_{31}^T \\ &= \cos \theta O_{11}^T + \sin \theta \cos \phi O_{21}^T + \sin \theta \sin \phi O_{31}^T\end{aligned}\quad (7)$$

## B. The structure of $Y$ and $Z$ matrices and Higgs couplings

We shall not discuss in detail the charge assignments, under the Abelian flavor symmetry, as many choices have appeared in the literature, e.g. Hermitian, non-Hermitian, etc. Rather, we shall present one form of a viable Yukawa matrices that shall be explored here. Namely, for up-type quarks we shall consider:

$$Y^u = \begin{pmatrix} \rho_{11}^u \lambda^4 & \rho_{12}^u \lambda^4 & \rho_{13}^u \lambda^4 \\ \rho_{21}^u \lambda^4 & \rho_{22}^u \lambda^2 & \rho_{23}^u \lambda^2 \\ \rho_{31}^u \lambda^4 & \rho_{32}^u \lambda^2 & \rho_{33}^u \end{pmatrix} \quad (8)$$

Very important, for the form of Higgs/Flavon couplings, is the fact that the 33 entry does not have a power of  $\lambda$ , which means that the Flavon coupling with the top quark will be suppressed, and will be of the same order as the coupling to charm quarks or the FV Higgs coupling with  $tc$ . We shall also assume that the Yukawa matrix for leptons ( $Y^l$ ) has a similar form as the d-type quark Yukawa matrix, which is given as:

$$Y^d = \begin{pmatrix} \rho_{11}^d \lambda^6 & \rho_{12}^d \lambda^6 & \rho_{13}^d \lambda^6 \\ \rho_{21}^d \lambda^6 & \rho_{22}^d \lambda^4 & \rho_{23}^d \lambda^4 \\ \rho_{13}^d \lambda^6 & \rho_{23}^d \lambda^4 & \rho_{33}^d \lambda^2 \end{pmatrix} \quad (9)$$

For leptons, we change  $\rho_{ij}^d \rightarrow \rho_{ij}^l$ . The choice for powers of  $\lambda$  is not unique, and in fact it could also change when the vevs ( $v_i$ ) of the Higgs doublets have a hierarchical structure.

We can also see that couplings to first generation quarks and leptons, is more suppressed, and thus in order to study the FV Higgs coupling, which is given by the matrices  $\tilde{Z}^f$ , we shall consider the 2-3 sub-system. Namely, for up quarks the  $Z$ -matrix, written in the quark mass eigenstate basis, is given by:

$$\tilde{Z}^u = \begin{pmatrix} Y_{22}^u & Y_{23}^u \\ Y_{23}^u & 2s_u Y_{23}^u \end{pmatrix} \quad (10)$$

and:

$$\tilde{Z}^d = \begin{pmatrix} 4Y_{22}^d & 4Y_{23}^d \\ 4Y_{23}^d & 2Y_{33}^d \end{pmatrix} \quad (11)$$

By performing a diagonalization to leading order in mixing angles ( $s_{u,d}$ ), one can go from the Yukawa parameters  $Y_{ij}^f$  to the diagonal ones  $\tilde{Y}_{ii}^f$ . Then, we find a relation among the parameters, such that we can express the  $\rho_{ij}^{u,d}$ 's in terms of the ratios of masses and the CKM angle  $V_{cb} \simeq s_{23}$ . Namely, we define:  $r_u = m_c/m_t$ ,  $r_d = m_s/m_b$ , and:  $r_1^u = Y_{22}^u/Y_{33}^u$ ,  $r_2^u = Y_{23}^u/Y_{33}^u$ . Similarly:  $r_1^d = Y_{22}^d/Y_{33}^d$ ,  $r_2^d = Y_{23}^d/Y_{33}^d$ . Within this approximation we have:  $\tilde{Y}_{33}^f \simeq Y_{33}^f$  for  $f = u, d$ . Then,  $r_1^f = r_f + r_2^f$ , and the ratios of Yukawas must satisfy the following relation:

$$r_2^u = r_2^d \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \quad (12)$$

Thus, we can vary  $r_2^d$ , and get values for  $r_1^d$ ,  $r_2^u$  and then  $r_1^u$ . Then to get the  $\tilde{Z}$  elements, we need to express the Yukawas  $Y_{33}$  in terms of the quarks masses, namely:  $Y_{33}^u = \sqrt{2}m_t/v_1$  and  $Y_{33}^d = \sqrt{2}m_b/v_2$ . Thus, we also need to specify the values of  $v_1$  and  $v_2$ ; a few interesting scenarios, are defined in the next sub-section.

### C. Parameter scenarios

Thus, in order to study the predictions of our model, we need to specify the vevs  $v_i$  and the rotation matrix for Higgs particles ( $O_{ij}$ ). We can take inspiration from the 2HDM results (see for instance [24]), which show that the LHC Higgs data favors both decoupling and alignment solutions, namely both  $\tan \beta \simeq 1$  and  $\tan \beta \gg 1$  are acceptable solutions. In terms of the Higgs vevs, this means that they are either of the same order or one is much larger than the other. Thus, we can explore the following cases for vev's, namely:

- We can fix first  $v_2 = v_3$ , which in spherical coordinates, means:  $\phi = \frac{\pi}{4}$ , and any value of  $\theta$ ,
- We could also consider vevs of the same order,  $v_1 \simeq v_2 = v_3$ , i.e.  $\theta \simeq \frac{\pi}{4}$ ,
- For hierarchical vevs, for instance  $v_1 \gg v_2 = v_3$ , i.e.  $\sin \theta \simeq \epsilon \ll 1$ .

Then, for the rotation matrix  $O$  of real components of scalar fields, we can identify several interesting scenarios:

1. The case where the 126-Higgs is lighter than the heavy Higgs particles and the flavons, i.e.  $m_h < m_{H_i} \simeq m_{H_F}$ ,
2. The case where the 126-Higgs is lighter than the heavy Higgs particles, which in turn are much lighter than the flavons, i.e.  $m_h < m_{H_i} \ll m_{H_F}$ ,

3. The case where the 126-Higgs is much lighter than the heavy Higgs particles, which are much lighter than the flavons, i.e.  $m_h \ll m_{H_i} \ll m_{H_F}$ ,

Here, we shall consider a special subcase of the first case, namely when the Flavon could be lighter than the Heavy Higgses, and it only mixes with the light Higgs; thus the mixing with the heavy Higgses is assumed to be much smaller. In this case, we have that the rotation matrix can be written as:  $O = \tilde{O}\hat{O}$ , where  $\hat{O}$  diagonalizes the  $3 \times 3$  subsystem for heavy Higgses and flavons, and has the form:

$$\hat{O} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_1 c_2 & s_1 c_2 & s_2 \\ 0 & R_{21} & R_{22} & c_2 s_3 \\ 0 & R_{31} & R_{32} & c_2 c_3 \end{pmatrix} \quad (13)$$

where:  $R_{21} = -c_1 s_2 s_3 - s_1 c_3$ ,  $R_{22} = c_1 c_3 - s_1 s_2 s_3$ ,  $R_{31} = s_1 s_3 - c_1 s_2 c_3$ ,  $R_{32} = -c_1 s_3 - s_1 s_2 c_3$ , and  $s_i = \sin \alpha_i$ ,  $c_i = \cos \alpha_i$ .

The rotation  $\tilde{O}$  takes care of the light Higgs-Flavon mixing, and is given by:

$$\tilde{O} = \begin{pmatrix} c_4 & 0 & 0 & s_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_4 & 0 & 0 & c_4 \end{pmatrix} \quad (14)$$

Then, for the case of equal vevs  $v_2 = v_3$  ( $\phi = \frac{\pi}{4}$ ), the relevant Higgs couplings are:

$$\begin{aligned} \chi_V &= \cos \theta O_{11}^T + \frac{\sin \theta}{\sqrt{2}} [O_{21}^T + O_{31}^T] \\ \eta^u &= \frac{O_{11}^T}{\cos \theta} \\ \eta^d &= \frac{\sqrt{2}}{\sin \theta} O_{21}^T \\ \eta^l &= \frac{\sqrt{2}}{\sin \theta} O_{31}^T \end{aligned} \quad (15)$$

where:  $O_{11}^T = c_4$ ,  $O_{21}^T = s_4 R_{31}$ ,  $O_{31}^T = s_4 R_{32}$  and  $O_{41}^T = s_4 c_2 c_3$ . The FV Higgs-fermion couplings factors are:

$$\begin{aligned} \kappa^u &= \frac{v}{u} O_{41}^T \cos \theta \\ \kappa^d &= \frac{v}{u} O_{41}^T \sin \theta \cos \phi \\ \kappa^l &= \frac{v}{u} O_{41}^T \sin \theta \sin \phi \end{aligned} \quad (16)$$

When we also assume:  $\theta_2 = -\theta_1$ , we have:  $R_{31} = s_1 s_3 + c_1 s_1 c_3$ ,  $R_{32} = -c_1 s_3 + s_1^2 c_3$ . Further, when also  $\theta_3 = 0$ , which means that the heavy higgses do not mix with the flavon, we get:  $O_{11}^T = c_4$ ,  $O_{21}^T = s_1 c_1 s_4$ ,  $O_{31}^T = s_1^2 s_4$  and  $O_{41}^T = c_1 s_4$ .

### III. FLAVOR CONSERVING HIGGS COUPLINGS AT LHC

The current data on Higgs production has been used to derive bounds on the Higgs couplings, which describe the allowed deviation from the SM. In particular, ref. [16] has derived bounds on the parameters  $\epsilon_X$ , which are defined as the (small) deviations of the Higgs couplings from the SM values, i.e.  $g_{hXX} = g_{hXX}^{SM}(1 + \epsilon_X)$ . We find very convenient, in order to use these results and get a quick estimate of the bounds, to write our parameters as:  $\eta^X = 1 + \epsilon_X$ . For fermions, the allowed values are:  $\epsilon_t = -0.21 \pm 0.23$ ,  $\epsilon_b = -0.19 \pm 0.3$ ,  $\epsilon_\tau = 0 \pm 0.18$ ; for W (Z) bosons these numbers are:  $\epsilon_W = -0.15 \pm 0.14$ ,  $\epsilon_Z = -0.01 \pm 0.13$ .

An extensive analysis of parameters satisfying these bounds will be presented elsewhere, with detailed numerical scans; here we shall pick a few specific points in parameter space, which satisfy the LHC bounds, and will help us to understand qualitatively the behaviour of the model. These points will also be used in the next section in our analysis of FCNC top decays. Thus, we show in figure 1,2 the predictions for each of these parameters, as function of the

angle  $\alpha_1$ , for the case with  $\phi = \frac{\pi}{4}$ ,  $\alpha_2 = -\alpha_1$  and  $\alpha_3 = 0$ . We can see that it is possible to satisfy these bounds for all the  $\epsilon$ 's.

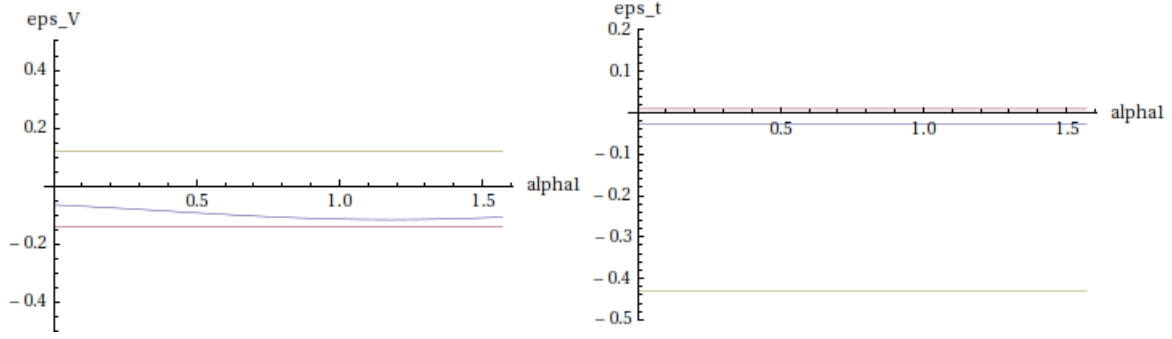


FIG. 1: Higgs coupling factors  $\epsilon_Z$  and  $\epsilon_t$  for the parameters of set 1. The horizontal lines are the experimental limits on these factors.

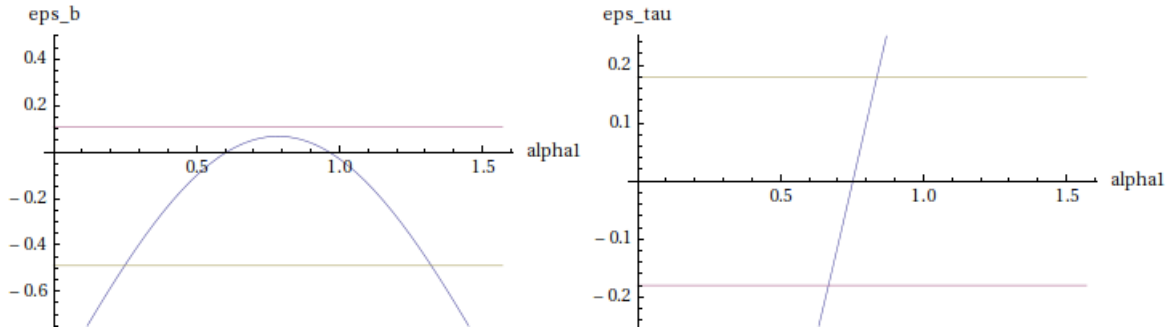


FIG. 2: Higgs coupling factors  $\epsilon_b$  and  $\epsilon_\tau$  for the parameters of set 1. The horizontal lines are the experimental limits on these factors.

One specific point, in agreement with all data, is :  $s_4 = 0.3$ ,  $\theta = 0.2$  and  $\alpha_1 = 0.7$ . For these values we have:  $\eta^u = 0.97$ ,  $\eta^d = 1.1$  and  $\eta^l = 0.89$  and  $\chi_v = 0.9$ . Then, using these values we can plot the Higgs-fermion coupling as function of the mass, which are shown in figure 2. We can see that the couplings for each fermion type lay on different lines, which could be distinguished from the SM (Black line), and all of them are in agreement with LHC Higgs data. Future measurements of these couplings at ILC will help us in order to discriminate between our model predictions and those of the SM.

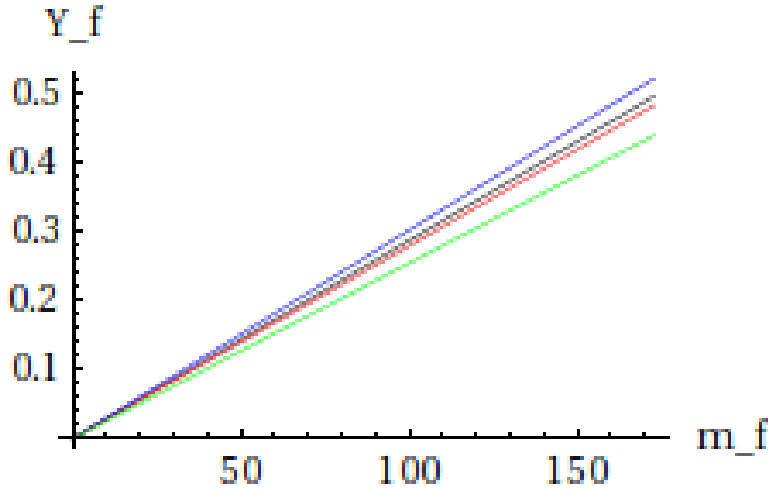


FIG. 3: The Higgs-fermion coupling factors as function of mass for the parameters of set 1. SM case (Black), up-type quarks (red), d-type quarks (blue), charged leptons (green).

As it will be shown in the next section, the diagonal corrections contained in the factors  $\kappa^f \tilde{Z}^f$ , will not change significantly the above discussion for the top quark-Higgs couplings. However, the Higgs coupling with the fermions ( $b\bar{b}, c\bar{c}, \tau^+\tau^-$ ), could be measured at next-linear collider (NLC) with a precision of a few percent, where it will be possible to test these effects. The corrections to the coupling  $h\bar{b}b$ , could modify the dominant decay of the light Higgs, as well as the associated production of the Higgs with b-quark pairs [28, 29].

#### IV. FV HIGGS COUPLINGS AND FCNC TOP DECAYS

##### A. Lessons from $\mathcal{L}_Y$ for FV Higgs couplings

The Yukawa sector predicts the presence of non-diagonal couplings (in flavor space), which can generate FCNC. However, we notice the following trends:

- The appearance of the factor  $v/u < 1$ , brings a suppression of the FV couplings, as compared with the FC ones,
- In the limit  $\cos \theta \rightarrow 1$ , which is one option to get a SM-like light Higgs boson, the factor  $\sin \theta \rightarrow 0$ , which appears in the FV Higgs couplings, will also give a suppression effect for d-type quarks and leptons, as compared with top quark, which is good because it will make easier to satisfy stronger bounds coming from  $K - K$  mixing and LFV transitions [26, 27].
- In general the mixing-angle factors ( $\eta$ 's) that enhance (suppreses) the FC Higgs interactions, will produce a supression (enhancement) the FV couplings ( $\kappa$ 's),
- The factor  $\sin \alpha_4 < 1$  will also induce another suppression effect,
- As we will show next, the Yukawa structure, which determines the form of the  $\tilde{Z}$  matrices will also induce additional suppression effects.

##### B. Numerical choice for $\tilde{Z}$ parameter

We shall consider the following sample values:  $r_d^2 = 0.05, 0.1, 0.3$ , and also assume:  $\cos \theta \simeq 1$ ,  $\sin \theta \simeq \epsilon$ , then table 1 shows the values of the entries for the  $\tilde{Z}^u$  matrix for the 2nd-3rd family case. We choose to focus on the up-quark sector, because we want to get an estimate for the most relevant predictions of the model, which we believe is related with the top quark physics, and in particular for the decay  $t \rightarrow c + h$ .

Scenario	$r_2^d$	$\tilde{Z}_{22}$	$\tilde{Z}_{23}$	$\tilde{Z}_{33}$
X	0.05	$3.5 \times 10^{-3}$	$1.1 \times 10^{-2}$	$2.6 \times 10^{-4}$
Y	0.1	$7.5 \times 10^{-3}$	$6.2 \times 10^{-2}$	$7.7 \times 10^{-3}$
Z	0.3	$7.2 \times 10^{-2}$	$2.6 \times 10^{-1}$	$1.5 \times 10^{-1}$

TABLE I: The entries 22,23 and 33 for the matrix  $\tilde{Z}^u$ 

Scenario	u[TeV]	$\kappa^u \times \tilde{Z}_{23}$	$B.R.(t \rightarrow ch)$
X1	0.5	$1.2 \times 10^{-4}$	$8.6 \times 10^{-9}$
X2	1	$6.1 \times 10^{-5}$	$2.2 \times 10^{-9}$
X3	10	$6.1 \times 10^{-6}$	$2.2 \times 10^{-11}$
Y1	0.5	$6.9 \times 10^{-3}$	$2.7 \times 10^{-5}$
Y2	1	$3.4 \times 10^{-3}$	$6.8 \times 10^{-6}$
Y3	10	$3.4 \times 10^{-4}$	$6.8 \times 10^{-8}$
Z1	0.5	$2.9 \times 10^{-2}$	$4.8 \times 10^{-4}$
Z2	1	$1.4 \times 10^{-2}$	$1.2 \times 10^{-4}$
Z3	10	$1.4 \times 10^{-3}$	$1.2 \times 10^{-6}$

TABLE II: The factor  $\kappa^u \times \tilde{Z}_{23}^u$  and Branching ratios for  $t \rightarrow ch$ 

For the specific point in parameter space, presented in previous section:  $\alpha_3 = 0$ ,  $s_4 = 0.3$ ,  $\theta = 0.15$  and  $\alpha_1 = 0.6$ , defined under the assumption:  $\phi = \frac{\pi}{4}$ ,  $\alpha_2 = -\alpha_1$ , which is in agreement with LHC data, we obtain the following value  $\kappa^u = 0.25 \frac{v}{u}$ . And with the entries  $\tilde{Z}^u$  shown in table 1, we obtain that the correction to the coupling  $h\bar{c}c$  could be of order 50 percent for  $\frac{v}{u} = 0.1$ , which could give some enhancement for the Higgs production through charm fusion, which could be worth further studying. On the other hand, the correction to the top quark-Higgs coupling is less than 0.1 percent, and thus negligible.

### C. The FCNC decay $t \rightarrow ch$

Top quark rare decays will enter into a golden era, because the LHC is a top factory, with about  $5 \times 10^6$  top pairs produced so far at the LHC. Thus, it is very interesting to look at the top decays that have some potential to be detectable. The first calculation of FCNC top decays at one-loop, was for  $t \rightarrow c + \gamma$  [39], while the complete calculations of the FCNC modes  $t \rightarrow cX$  ( $X = \gamma, g, Z, h$ ) was reported in ref. [40]. Then, the calculation for the mode  $t \rightarrow ch$ , was corrected in [41, 42]. In turn, the FCNC decays into pairs of vector bosons  $t \rightarrow cW^+W^- (ZZ, \gamma\gamma)$ , was presented in: [43–46]. The mode  $t \rightarrow c\ell^-\ell^+$  was discussed in [47, 48]. All of these modes have an extremely suppressed BR within the SM, but they have an enhanced BR when New Physics (NP) is involved, see for instance [49]. More promising, in terms of having a larger BR is the mode  $t \rightarrow bW\ell^-\ell^+$ , which was studied recently [50].

Here we shall focus on the mode  $t \rightarrow ch$ , which can reach large BR's. The decay width is given by:

$$\Gamma(t \rightarrow ch) = \frac{m_t}{6\pi} |\kappa^u \tilde{Z}_{23}|^2 \quad (17)$$

Under the approximation that the top decay  $t \rightarrow b + W$  dominates the total width, and it is given by the SM result  $\Gamma(t \rightarrow b + W) \simeq 1.5$  GeV, we obtain:  $BR(t \rightarrow ch) = 0.58 |\kappa^u \tilde{Z}_{23}|^2$ . For  $v/u = 0.25$ , and the values of parameters called scenario Z in table 1, one finds that the B.R. reaches a value  $BR \simeq 1.5 \times 10^{-4}$ , which is about 9 orders of magnitude above the SM prediction; and moreover it can be tested at LHC [51]. Values of BR for other choices of parameters, using the results of table 1 are shown in table 2. The labels X1,X2,X3 correspond to the choices of  $u = 0.5, 1, 10$  TeV, within scenario X of Table1, and similarly for Y1,Y2,Y3 and Z1, Z2, Z3.

## V. CONCLUSIONS AND OUTLOOK

One of the most important tasks of future colliders is to study the properties of the Higgs-like particle with  $m_h = 125 - 126$  GeV discovered at the LHC. Current measurements of its spin, parity, and interactions, seem consistent with the SM, where its couplings to fermions and gauge bosons are proportional to the particle mass. We have studied the variations on these couplings, within a model with extended Higgs sector, where the masses for each fermion type,



arise from a different Higgs doublet. This model also includes mixing of the Higgs doublets with a Flavon field, which generates the Yukawa hierarchies and induces Flavor-violating Higgs couplings at acceptable rates. Constraints on these couplings, derived from Higgs search at LHC, and their implications for FCNC top decay  $t \rightarrow ch$ , were discussed too. We find that this mode could reach a BR of order  $10^{-4}$ , which could be studied at LHC. In the down-quark and lepton sectors, there are also interesting aspects to study in the future, such as the rates for rare b-decays. or the decay  $h \rightarrow \tau\mu$  can be induced at rates that could be detected at future colliders. The complementarity of future colliders has been studied in [52].

There are two aspects of our model that give some hope to measure the Higgs couplings with light fermions, namely Dark matter and LFV. In the case of DM, it is possible that its interaction with nucleons could be mediated by the higgs boson, which depends on the strength of the Higgs interaction with nucleons, which in turn depends on the Higgs coupling with light fermions. Therefore, by searching for DM-nucleon dispersion, one is also testing the Higgs coupling with light quarks. Similar remarks hold when one considers  $e - \mu$  conversion, where the Higgs nucleon interaction appears. Thus, nature could be extra benevolent, and besides showing evidence of the new physics, it will allow to test the couplings of light quarks with Higgs.

However, the most salient feature of this model is the Flavon field, which has FV couplings with fermions. Within the scenarios discussed here, the 4th Higgs boson  $H_F$  is dominated by its Flavon ( $S_1$ ) component. The size of its coupling with top quarks, will be given by the factor  $\kappa_4 \tilde{Z}_{33}^u$ , where:  $\kappa_4 = c_4 \cos\theta v/u$ , which is of order 0.1 for  $v/u = 0.1$ , while  $\tilde{Z}_{33}^u \simeq 0.1$  (within scenario that we called set 1). Thus, we will have a coupling of order  $10^{-2}$  (compare with the SM top-Higgs coupling which is of order 0.7). Thus  $H_F$  could be produced through gluon fusion (top loop), with a cross-section of order  $3 \times 10^{-4}$  times the SM Higgs cross section. Despite the fact that the cross section seems quite suppressed, one has the advantage of the clean signature of Flavon decays, such as the LFV mode  $H_F \rightarrow \tau\mu$ , which will have a B.R. similar to the ones for the FC modes. A detailed study of this mechanism at the VLHC with 100 TeV c.m. energy is underway [53].

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